RUE - 12

CENTRO DE MODELAMIENTO MATEMATICO

INFORME ANUAL DE PROYECTO[1]
APOYO COMPLEMENTARIO DE CONTRAPARTE PARA PROYECTOS DE COOPERACIÓN INTERNACIONAL APROBADOS POR UNIÓN EUROPEA

Programa Bicentenario de Ciencia y Tecnología

Proyecto VI Programa Marco:

MODURBAN

MODULAR URBAN GUIDED RAIL SYSTEMS
FP6-PLT-516380

Noviembre de 2006

Penodo 2006

[1] El presente informe contiene informaciones y datos relativos al Proyecto MODURBAN, del VI Programa Marco de la Unión Europea, y está por lo tanto sujeto a condiciones estrictas de reserva y confidencialidad.

CONTENIDO

I. INTRODUCCIÓN

Investigadores chilenos participantes:

Jorge Amaya, U. de Chile
Rafael Correa, U. de Chile (responsable)
Roberto Román, U. de Chile

Entidades europeas participantes en el subproyecto:

Alstom (Francia)
Siemens (Alemania)
Ratp (Francia)
Bombardier (Alemania)
Merak (España)
Ansaldo Breda (Italia).

La lista completa de participantes, así como otras informaciones del proyecto, pueden ser vistas en: http://www.modurban.org/

Formación de investigadores:

Han participado activamente, además de los investigadores senior, dos investigadores jóvenes:

Guillermo Poblete (Ingeniero Civil en Computación, Universidad de Chile)
José Antonio Sánchez (tesista de Ingeniería Civil Mecánica, Universidad de Chile)

Estos dos investigadores han adquirido un *expertise* de alto nivel en el tema de modelamiento de ventilación en túneles y carros de Metro y transporte por trenes en general. Ambos continúan en el proyecto por el año 2007 y se prevé que viajen a Europa durante el año para realizar pasantías en algunas de las empresas europeas involucradas.

El producto y su propiedad intelectual:

El principal producto de esta etapa es un software de Balance Termal para simulación y análisis de ambiente al interior de túneles y carros de Metro. Los resultados de este producto, aplicados a casos específicos fueron presentados en la reunión realizada en la Universidad de Chile los días 2-3 de noviembre 2006, a la cual concurrieron expertos de las contrapartes europeas (Alstom, Siemens, Merak y Ratp). Se aplicó a los casos reales de los sistemas de Metro de París, Madrid y Barcelona. Se prevé una aplicación sobre el caso de Santiago, pero esto depende de un acuerdo con la empresa, en relación al uso de los datos.

El software está en etapa final (se afinan mejoras producto de la última reunión en Chile) y es materia de protección intelectual, aunque debe considerarse en copropiedad con los socios del proyecto europeo. Este producto ha sido generado completamente en Chile, tanto en los aspectos del modelo físico-matemático como la programación computacional, incluyendo las interfaces de usuario.

La primera versión se entregó oficialmente, tanto a los miembros del Consorcio como a la Comisión Europea, en junio de 2006. Paralelamente, el CMM mantiene la página Web www.cmm.uchile.cl/modenergy, de acceso restringido a los miembros del Consorcio, en la cual reside la versión actualizada a octubre 2006, completamente operativa y en uso actualmente por los miembros del Consorcio involucrados en el producto. A través de esta página y de un Blog creado para ese efecto, los miembros del equipo en Chile interactúan con los participantes europeos.

Movilidad:
Durante el año 2006, se han realizado en Europa las siguientes reuniones de avance del proyecto, a las cuales han concurrido dos investigadores chilenos cada vez:

París (Ratp): 23-24 de febrero
Madrid (Merak): 22-23 de junio

La tercera reunión se realizó en Santiago, los días 2-3 de noviembre, con costos a cargo del proyecto chileno. La próxima reunión está prevista para los días 6-7 de febrero, 2007, en los locales de Ansaldo Breda (Italia). A ella concurrirán al menos tres miembros del equipo del CMM.

Difusión al medio nacional:
Como parte de la inserción de los resultados del proyecto en nuestro país, el equipo de trabajo tomó contacto con la empresa Metro de Santiago, que derivó en un estudio que actualmente se está realizando en el CMM, sobre la temática: "Análisis del efecto de instalar un sistema de intercirculación entre coches". Esta investigación se orienta a simular y describir el comportamiento de los flujos de aire al interior de los carros, como una forma de proponer modificaciones que permitan una mejor ventilación. Esta es una línea de trabajo que se está abriendo a nivel nacional, y que permitirá realizar en el futuro la transferencia de algunos resultados del proyecto Modurban al medio nacional.

En la reunión realizada en el CMM en noviembre 2006, se acordó iniciar gestiones tendientes a invitar al Metro de Santiago al Consorcio del proyecto Modurban. Este es un proceso que puede tomar algún tiempo, pero se espera al menos realizar la aplicación de nuestro software a datos de Santiago, durante en el año 2007.

El apoyo del Programa Bicentenario de Ciencia y Tecnología
El soporte del PBCT al desarrollo del proyecto MODURBAN en Chile ha permitido, por una parte, facilitar la movilidad de los investigadores (cuestión esencial en este tipo de proyectos internacionales) y, por otra, posibilitar la formación de recurso humanos, a través de la participación de jóvenes investigadores. Otro aspecto importante es la relación que se ha establecido entre esta unidad académica ejecutora y una importante empresa nacional (Metro de Santiago), a través de un proyecto específico de colaboración, actualmente en desarrollo.

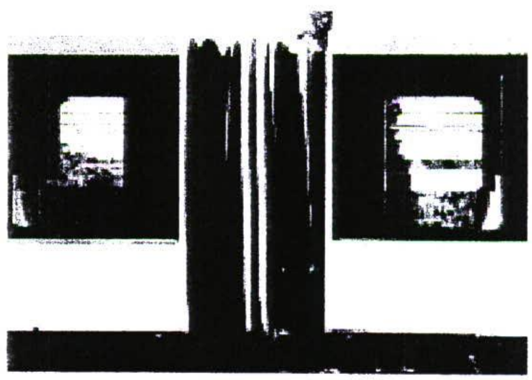
II. ANÁLISIS DEL EFECTO DE INSTALAR UN SISTEMA DE INTER-CIRCULACIÓN ENTRE COCHES DEL TREN NS-74 (en desarrollo con Metro de Santiago)

1 El estudio

Se busca mejorar las condiciones de ventilación en los trenes NS-74. Esto es, determinar los beneficios que implicaría en términos de confort, la mejora en la ventilación de los coches. En general el objetivo es mejorar la calidad de servicio y adaptar los trenes NS-74 a estándar de los trenes NS-93 que poseen intercirculación entre coches (tren Boa).

Con la simulación se espera determinar:

- Efectos en la temperatura
- Efectos en la sensación térmica al interior de los coches a distintos niveles de carga.
- Efectos en la renovación del aire en los coches.
- Contrastar con las condiciones del tren NS-93 y establecer las desviaciones.



2 Actividades del estudio

Para concretar el objetivo del estudio se requiere realizar mediciones reales en los trenes de temperatura, del flujo del aire al interior del coche y de cualquier otra variable necesaria para efectuar la simulación, en los trenes NS-74 y NS-93. Para evitar la turbulencia entre los coches se debe considerar estanqueidad entre un coche y el otro (suponer un fuelle estanco entre éstos). Las actividades son:

- Realizar mediciones reales en los trenes (temperatura, flujo del aire, etc.) en los trenes NS-74 y NS-93
- Simular el efecto de reemplazar las puertas actuales de los trenes NS-74 por puertas "permeables" (con celosías o rejilla que permitan el paso del aire entre los coches)
- Simular la situación actual de los trenes NS-93 para contrastar con el tren NS-74

- Simular la situación considerando la instalación de un sistema mejorado de ventilación entregado por Metro en el tren NS-74, distinto a la modificación de los pasillos

3 Resultados y productos ofrecidos.

- Descripción y antecedentes del problema investigado, hipótesis y supuestos de modelación
- Simulaciones y resultados computacionales
- Conclusiones y recomendaciones.

III. MANUAL TÉCNICO DEL SISTEMA MODENERGY:
Simulador de Balance Termal en Túneles de Metro

Project: MODURBAN

FP6 Project: IP 516380
EC Contract n°: TIP4-CT-2005-516380

Subproject: MODENERGY

WORKPACKAGE WP16:
Prescription for HVAC's in a total system approach and development of an advanced optimization software to reduce energy consumption

Document title: THERMAL BALANCE MODEL

Prepared by:

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Date: October 26, 2006

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Abstract

This document contains the basic assumptions and equations to describe the thermal balance model in a metro system. This model is based on a system of equations, arising from classic mechanics and designed to be a part of a more detailed energy efficiency model.

The goal of this model is to provide a rigorous justification for the construction of a software tool for simulation and optimization of a general metro line system.

The software can be used to study the behavior of energy and heat exchanges in the tunnel, in order to propose efficient solutions for passengers comfort.

Contents

1 Introduction

A train that runs on tracks out in the open does not significantly changes the thermal balance of the environment. The losses that it dissipates do not affect the outside conditions in a measurable way.

But external conditions can and do affect the interior environment in a train. In effect, heat gained by radiation through glazing or by indirectly heating up the train skin can significantly impact the interior conditions.

In a tunnel system the situation is quite different. The energy exchanges between the train and surroundings can significantly change ambient conditions. The model described in this document permits the analysis of this phenomenon in the following ways:

- *Energy balances:* to categorize energy exchanges and properly identify the impact on energy consumption as well as thermal balance.
- *Prediction of ambient conditions:* identify the conditions that will lead to uncomfortable situations in a metro line.
- *Evaluation of the impact of changes in the system:* how a change in operation, technology or other variables can affect energy expenditure in the system.

2 The Model

The whole system can be conceived as a series of nodes interconnected by tracks. Each node is a station and the tracks link these stations. We assume that energy flows as electrical energy into electrical substations that are located at given places. From these substations a large amount of energy is injected into the train system, including ventilation and auxiliaries.

From an electrical point of view, there are essentially two systems: the first one is the train, auxiliaries and traction power; the second one is a standard three phase system for stations, control and ventilation. The first one is a direct current system and the second one is alternating current. These systems can be considered as isolated.

From a thermal and mass transfer point of view the systems are interconnected. Normally air enters stations, flows along corridors, platforms and tunnels, to be evacuated at ventilation stations inside the tunnel. Air gains heat and moisture from waste heat in the system and moisture released by passengers and other water sources. Heat is extracted from the system by:

- Sensible and latent heat carried away by exhaust air.
- Sensible heat transferred to the earth surrounding the tunnels.

Nevertheless, from a thermal point of view, each track section is isolated from the rest of the line, and this generic situation is extended to the general system. So when we analyze a whole line, it will simply be the sum of track sections between stations.

Thus a line will be a series of nodes that represent stations linked by tracks between them. Each track shall have the actual length between stations as well as the specific slope and curvature. Stations also have a specific length and temperature, representing boundaries conditions for the calculation tool.

Therefore the whole system will be a sequence of nodes (stations) interconnected by arcs.

3 Thermal Balance

For the analysis, we first see what happens with a single train from one given station to the next one. A train along a section of track has a distinct speed versus distance trajectory, that is defined by the system operator.

Inside the tunnel we have to consider the following elements:

- Train: is a thermal energy source. This energy comes from: rolling and air friction, braking losses, auxiliary power dissipated into the tunnel and passenger thermal load.
- Air in tunnel: it heats up in response to the thermal energy dissipated by successive trains. It is also a sink as it is evacuated from the tunnel.
- Earth around tunnel: it is a thermal sink, since it can absorb energy from the air.

The heat flow generated by the train ($\dot{Q}_T$), in W, can be decomposed in the form:

$$\dot{Q}_T = \dot{Q}_A + \dot{Q}_G \tag{1}$$

where:

$\dot{Q}_A$ = heat flow absorbed by air, in W
$\dot{Q}_G$ = heat flow absorbed by ground, in W

The final goal is to calculate the air temperature inside the tunnel. To achieve that, the heat overall exchange must be calculated.

The tunnel is divided in discrete segments of length Δx, where the speed and the air temperature are assumed constant, generating control volumes where the thermal balance could be calculated, as shown below in equation (2). The terms in Figure 1 are:

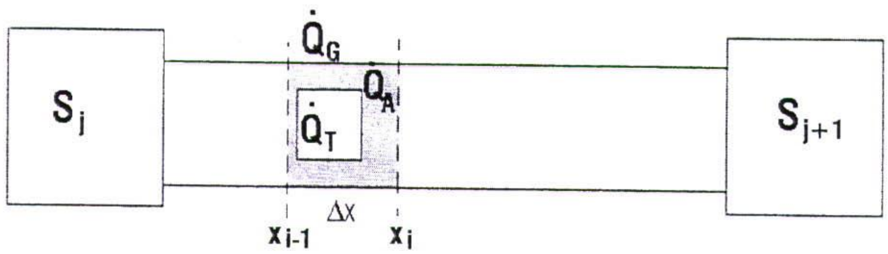

Figure 1: *Thermal balance model*

Δx = length of segment in m

x_i = actual position of train in the x-axis

x_{i-1} = previous position of train in the x axis

S_{j+1} = next station

S_j = actual station

and we consider the following assumptions:

- A train is a car array
- Each car has its own properties
- We assumed mean values for what happen up and downstream the train midpoint.
- The train midpoint concured whit the stations midpoint.
- Trains are accelerating or braking by the time they enter or exit the tunnel.
- Heat generated by the trains, as well as the third rail, is dissipated to the air in the tunnel.
- Air transfer heat by convection to the tunnel walls and floor.
- Heat is transferred to the ground by conduction.

- Radiative exchanges (short wave), between train and tunnel, are assumed to be negligible.

The total thermal load along a section of track will depend on how many trains pass during a given time interval, the type of the train, its speed and the amount of transported passengers. In order to stabilize the flows inside the tunnel, we consider a one hour regimen, with constant frequency. The total heat generated by the trains (in both directions) is:

$$\dot{Q}_G + \dot{Q}_A = \frac{f}{3600}(Q_{T_1} + Q_{T_0}) \tag{2}$$

where:

Q_{T_1} = heat generated by one train running on one direction
Q_{T_0} = heat generated by one train running on the other direction
f = trains per hour

4 Heat Flow to Air ($\dot{Q}_A$)

Air heat flow is calculated with equation (3), using stations temperatures [8], as shown in figure 2.

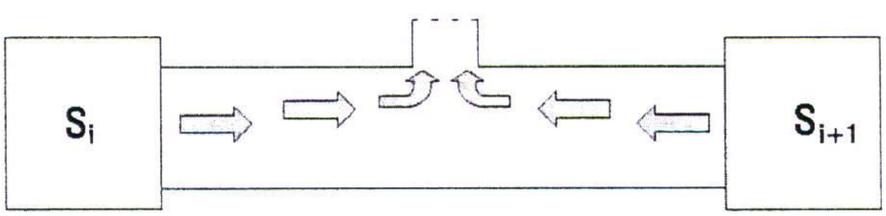

Figure 2: *Air flow inside the tunnel*

Air flow inside the tunnel is considered as an input and must obtained taking in to account that, air flows along the axis of the tunnel by three effects: first, by the air extractor system;

second, by the piston effect of the trains; third, by chimney effect due to different air densities between the tunnel and external ambient air, as well as different elevations of stations.

$$\dot{Q}_A = \dot{w}_A \rho_A C_{p,A}(T_i - T_{i-1}) \tag{3}$$

where:

$\dot{w}_A$ = air flow inside the tunnel taking in to account air renovation, in m^3/s

ρ_A = air density = 1.177 kg/m^3

$C_{p,A}$ = air specific heat = 1007 $J/(kgK)$

T_i = air temperature at x_i, in $°C$

T_{i-1} = air temperature at x_{i-1}, in $°C$

Air properties change according to the pressure and temperature inside the tunnel but, at the temperature range that we are working, this properties do not varied significantly. We display below the typical values used (for atmospheric pressure and 300 $°K$):

- air kinematic viscosity (μ) = 1.857 $kg/(ms)$
- air thermal conductivity ($\lambda_{A,T}$) = 0.02623 $W/(mK)$

5 Heat Flow to Ground ($\dot{Q}_G$)

Earth temperature at the wall of the tunnel depends firstly on the heat transfer from earth surface to deeper layers. Secondly the air in the tunnel itself influences the earth temperature at the tunnel wall [2].

The calculations are based on approximations for the earth temperature which varies with the season of the year and depth under surface. Heat transfer coefficients for the heat flow between air, tunnel wall and earth are estimated from material coefficients, flow properties and geometric parameters. The following restrictions are made for the current version of the program:

- homogeneous earth is situated above and around the tunnel

- ground properties are constant

For to calculate the heat exchange in the tunnel the total length of the tunnel is divided into segments which are treated step by step. Each segment is supposed to carry air of constant temperature so that heat exchange in the segment leads to a jump in temperature at the border between two segments. The heat exchange for each segment is:

$$\dot{Q}_G = \Delta x U_L \left(T_i - T_{E,W} \right) \tag{4}$$

where:

Δx	= length of the segment, in m
U_L	= heat transfer factor per length of wall between bulk air and wall, in $W/(mK)$
T_i	= air temperature at x_i, in $°C$
$T_{E,W}$	= earth temperature at the wall of the tunnel, in $°C$

It is necessary to introduce a correction factor [4] to represent the influence of the tunnel on the earth temperature. Then, comparing the heat flow from the earth surface to the tunnel, with the heat flow through the tunnel wall [3], the corrected earth temperature at the wall of the pipe is:

$$T_{E,W} = \frac{U^* T_{E,0} + T_i}{U^* + 1} \tag{5}$$

where U^* is the conductance ratio of heat transfer from earth surface to tunnel and from airflow to tunnel wall.

This parameter U^* is defined to take into account thermal conductivity of the earth, heat transfer coefficient between the airflow and the earth at the tunnel wall as well as the geometric configuration:

$$U^* = \frac{2\pi\lambda}{U_L} \frac{1}{\ln\left(\frac{S_0}{R_0} + \sqrt{\left(\frac{S_0}{R_0}\right)^2 - 1} \right)} \tag{6}$$

with:

λ = ground thermal conductivity = 1.5 $W/(mK)$

S_0 = depth of tunnel center under surface, in m

R_0 = hydraulic radius of tunnel, in m

The heat transfer coefficient per length of wall of tunnel U_L depends only on h_i, the heat transfer coefficient at the inner surface of the tunnel, in the form:

$$U_L = 2\pi R_0 h_i \tag{7}$$

The heat transfer coefficient at the inner surface of the tunnel h_i (which is measured in $W/(m^2K)$) depends on flow properties, dimensions of the tunnel and material properties of the air in the tunnel [2], in the form:

$$h_i = \frac{\lambda_{A,T} Nu}{2R_0} \tag{8}$$

The Nusselt number Nu of air in a pipe depends on Reynolds number R_e and thus on flow rate. For turbulent airflow Gnielinski [ ] proposes the following approximation:

$$Nu = 0.0214(R_e^{0.8} - 100)P_r^{0.4}$$

with:

P_r = Prandtl number of air

R_e = Reynold number

The Reynolds number is basically the ratio of the inertial force of the medium over it viscous force.

$$R_e = \frac{2\rho V_a R_0}{\mu}$$

where V_a is air speed. The Prandtl number of air is taken as a constant (typically $P_r = 0.72$).

$$P_r = \frac{C_p \mu}{\lambda_{A,T}}$$

The earth temperature at the wall of the tunnel not influenced by the tunnel (denoted $T_{E,0}$) is calculated from the ambient air temperature with its mean value T_m and its maximum value T_{max}, assuming a sinusoidal temperature variation throughout the year.

$$T_{E,0} = T_m - (T_{max} - T_m)e^{-\xi}cos(A - \xi) \tag{9}$$

A parameter ξ describes the "thermal depth" of the tunnel. Heat flows from air to earth surface without resistance.

$$\xi = S_0\sqrt{\frac{\pi \rho_c}{t_0 \lambda}}$$

where:

A = season constant (A=0 for summer and A=0.5 for winter)

ρ_c = volumetric heat capacity of ground, in J/m^3K

t_0 = duration of year, in s (1 year = 31.5×10^6 s)

6 Train Heat (Q_T)

The heat generated by a train can be split in four terms, according on accelerating rate, the use of brakes, friction loses and constant heat values related with the passenger load, use of auxiliaries and others.

Equation 10 shows the different train heat sources.

$$Q_T = T_{raction} + B_{rakes} + F_{riction} + O_{thers} \tag{10}$$

6.1 First train heat term ($T_{raction}$)

Electric and mechanical inefficiencies are taking in to account as the train increases its acceleration. $T_{raction}$ are energy loses related with the differences between the motors electrical power consumption and power necessary for motion.

The train was modeled as a dynamic system that moves along rails. The train has a certain mass (tare weight, load and rolling inertial mass). Forces that act on the train are:

inertia, rolling friction, air drag, forces due to curvature and forces due to slope. From the equations one can calculate the required force for the train to accelerate and thus the input power as well as the energy losses.

$$T_{raction} = \left(\frac{P_{ower}}{\eta} - P_{ower}\right)\Delta t$$

with:

P_{ower}	= mechanical power for motion in W
η	= electrical motor efficiency

The way the Power is calculated is further explained.

6.2 Second train heat term (B_{rakes})

As the train brakes one part of the energy needed to decrease its speed is re injected to the lines and the other is dissipated as heat.

In this situation we have two cases. The first on consider only the work of regenerative brakes and the braking efficiency related to it.

$$\begin{aligned} B_{rakes} &= \Delta E_k(x_i) + \Delta E_p(x_i) - R_E \\ B_{rakes} &= \left|\Delta E_k(x_i) + \Delta E_p(x_i)\right| (1 - RECOV) \end{aligned}$$

with:

R_E	= recovered energy, in J
$RECOV$	= recovery rate, $0 \leq e \leq 1$
$E_k(x_i)$	= kinetic energy at x_i, in J
$\Delta E_p(x_i)$	= potential energy difference at x_i, in J

These energy terms are calculated as:

$$\begin{aligned} E_k(x_i) &= \frac{1}{2} M_T V^2(x_i) \\ \Delta E_p(x_i) &= g \sum M_{W,i} \frac{dh(i)}{dl(i)} \Delta x \\ M_T &= \sum M_{W,i} \end{aligned}$$

where:

$dh(i)$ = track hight difference with equal slope for a particular wagon in m

$dl(i)$ = track length with equal slope and curve radius for a particular wagon in m

$M_{W,i}$ = mass of wagon i, in kg

The second case, suppose that for a particular speed regenerative brakes are almost useless and mechanical breaks are used. Thus this specific speed is considered as input.

$$B_{rakes} = |[E_k(x_i) - E_k(x_{i-1})] + \Delta E_p(x_i)|$$

where:

$E_k(x_{i-1})$ = kinetic energy at x_{i-1}, in J

6.3 Third train heat term ($F_{riction}$)

This term considers friction from wheels to rails or train to air. The amount of energy dissipated on friction is calculated as the power wasted due to Aerodynamic Drag Forces and Curve Forces, plus the Rolling Friction Force work.

$$F_{riction} = (F_D + F_C)\, V(x_i) \Delta t + F_R \Delta x$$

where:

F_D = drag force, in N

F_R = rolling friction force, in N

F_C = curve force, in N

$V(x_i)$ = train speed at x_i, in m/s

The way this forces are calculated is further explained.

6.4 Fourth train heat term (O_{thers})

The fourth term considers the heat generated by electrical auxiliaries (lights, ventilators, cooling systems and other electrical systems), passengers and thermal losses from the third rail or joule losses in motors and other electrical elements.

$$Others = Pass + Aux + T_R + M_C$$

with:

$Pass$	$=$ passengers thermal load, in W
Aux	$=$ electrical auxiliaries, in W
T_R	$=$ third rail effect, in W
M_C	$=$ melting of conductors, in W

Each passenger is a thermal load of about 110 $Watts$, therefore the total load will be:

$$Pass = NQ_{pass}$$

where N represents the number of passengers and Q_{pass} a single passenger thermal load, in W.

Auxiliaries (lights, ventilation and HVAC systems), is assumed to be constant in each car. In order to perform the calculations we use the average Auxiliaries value.

The third rail effect or joule effect, depends on the line electrical resistance, which varies with the distance from the nearest electrical substation.

$$T_R = R(x_i)I^2$$

with:

$R(x_i)$	$=$ line electrical resistance in Ω
I	$=$ current intensity in A

As a formalism we include the heat generated by the melting of the conductors, but we consider this term to be irrelevant for our calculations:

$$M_C = \frac{M_{lost}}{3600} C_L$$

with:

M_{lost} = mass lost in conductors per hour, in $kg/hour$
C_L = conductors material latent heat, in J/kg

6.5 Power calculations

In order to achieve a specific speed, the train has to overcome all the forces that are against its motion. Therefore the inlet power can be conceived as the result of multiplying this forces with the train speed and adding the power waste in to Rolling Friction work

$$\begin{aligned} P_{ower}(x_i) &= F(x_i)V(x_i) + \frac{F_R \Delta x}{\Delta t} \\ F(x_i) &= F_I(x_i) + F_D(x_i) + F_C(x_i) + F_S(x_i) \end{aligned}$$

where:

$P_{ower}(x_i)$ = power generated by the motors at x_i, in W
$F(x_i)$ = forces over the train at x_i, in N

The force needed to accelerate the train can be broken down into the following components:

- Inertial Forces (F_I). To move forward, the train must provide enough energy to overcome the train inertia, which is directly related to its weight.

$$F_I = (M_T + M_I)a(x_i)$$

where:

M_I = train inertial mass, in kg
$a(x_i)$ = train acceleration, in m/s^2

- Rolling Friction Force (F_R). It is conceived, as force necessarily to move the wheels forward and is directly proportional to the weight of the load supported by the wheels. The magnitude of the friction force is [6]:

$$F_R = M_T g K_1$$

where:

F_R = rolling friction force in N
K_1 = kinematic friction coefficient
g = gravity acceleration in m/s^2

- Aerodynamic Drag (F_D). The force exerted on a train moving inside a tunnel, depends in a complex way upon the velocity of the train relative to the air, the viscosity and density of air, the shape of the train, the roughness of its surface and the tunnel cross-sectional area [7].

$$F_D = \frac{1}{2} A_F C_D \rho_A V^2(x_i) \alpha_T$$

with:

F_D = aerodynamic drag force N
A_F = train frontal area m^2
C_D = drag coefficient
α_T = tunnel parameter

For small values of the Reynolds number (called laminar flow since the flow is nonturbulant) the drag coefficient is inversely proportional to the velocity. This means that the drag force is only proportional to the train velocity.

When the flow is turbulent the Reynolds number is large, and the drag coefficient C_D is approximately constant. This is the quadratic model of fluid resistance, in that the drag force is dependent on the square of the velocity.

- Force due to Track Curve (F_C). These force is a result of the change in the accelerating vector.

$$F_C = V^2 \sum M_{W,i} \frac{1}{r_{(i)}}$$

with:

F_C = force due track curve in N
V = train speed at x_i in m/s
r = curve radius for a particular wagon in m

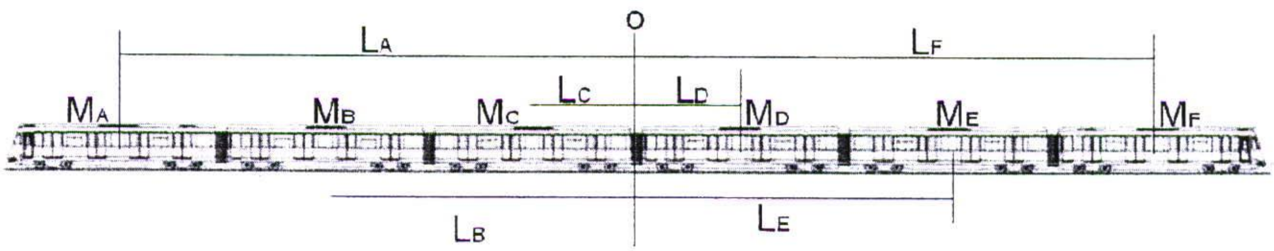

Figure 3: *Example sketch of train model*

In the example, the force due curve, is calculated as shown:

$$V^2_{(o)} \left[M_A \frac{1}{r_{(o-L_A)}} + M_B \frac{1}{r_{(o-L_B)}} + M_C \frac{1}{r_{(o-L_C)}} + M_D \frac{1}{r_{(o+L_D)}} + M_E \frac{1}{r_{(o+L_E)}} + M_F \frac{1}{r_{(o+L_F)}} \right]$$

- Force due to Track Slope (F_S). Not always this force plays against motion. It depends on the direction in which the train is moving, down or up stream.

$$F_S = g \sum M_{W,i} \frac{dh(i)}{dl(i)}$$

with:

F_S = force due track slope in N

As shown in figure 3, in order to evaluate the slope force we used the approximation:

$$g\left[M_A\frac{dh_{(o-L_A)}}{dl_{(o-L_A)}}+M_B\frac{dh_{(o-L_B)}}{dl_{(o-L_B)}}+M_C\frac{dh_{(o-L_C)}}{dl_{(o-L_C)}}+M_D\frac{dh_{(o+L_D)}}{dl_{(o+L_D)}}+M_E\frac{dh_{(o+L_E)}}{dl_{(o+L_E)}}+M_F\frac{dh_{(o+L_F)}}{dl_{(o+L_F)}}\right]$$

7 References

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[3] K.J. Albers, *Untersuchungen zur Auslegung von Erdwärmeaustauschern für die Konditionierung der Zuluft für Wohngebäude*, Ph. D. Thesis, Universität Dortmund, Dortmund, 1991.

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[5] V. Gnielinski, *Neue Gleichungen für den Wärmeund den Stoffübergang in turbulent durchströmten Rohren und Kanälen*, Forschung im Ingenieur-Wesen, 41, 1975.

[6] Dan B. Marghitu, *Mechanical Engineer's Handbook*, ACADEMIC PRESS, 2001.

[7] Edward H. Smith, *Mechanical Engineer s Reference Book*, Buttenvorth-Heinemann,Twelfth edition, 2000.

[8] John H. Lienhard IV and John H. Lienhard, *Mechanical A Heat Transfer TextBook*, Phlogiston Press,Third edition, 2000.

List of notations

Simbol	Description
$\dot{Q}_T$	= heat flow generated by the train in W
$\dot{Q}_A$	= heat flow absorbed by air in W
$\dot{Q}_G$	= heat flow absorbed by ground in W
Δx	= length of segment in m
x_i	= actual position of train in the x axis
x_{i-1}	= previous position of train in the x axis
S_{j+1}	= next station
S_j	= actual station
Q_{T_1}	= heat generated by train running on one direction in J
Q_{T_0}	= heat generated by train running on the other direction in J
f	= frequency of trains per $hour$
3600	= 1 hour in s
$\dot{w}_A$	= air flow inside the tunnel taking in to account air renovation in m^3/s
ρ_A	= air density in kg/m^3
$C_{p,A}$	= specific heat of air $J/(kgK)$
T_i	= air temperature at x_i $°C$
T_{i-1}	= air temperature at x_{i-1} $°C$
Δx	= length of the segment in m
U_L	= heat transfer coefficient per length of wall of tunnel between bulk air and wall in $W/(mK)$
T_i	= air temperature at x_i in $°C$
$T_{E,W}$	= earth temperature at the wall of the tunnel in $°C$
$U*$	= conductance ratio of heat transfer from earth surface to tunnel and from airflow to tunnel wall
λ	= ground thermal conductivity in $W/(mK)$ (typically: $\lambda = 1.5\ W/(mK)$

Simbol	Description
S_0	= depth of tunnel center under surface in m
R_0	= hydraulic radius of tunnel in m
h_i	= heat transfer coefficient at the inner surface of the tunnel in $W/(m^2K)$
P_r	= air Prandtl number
R_e	= Reynold number
V_a	= air speed
A	= season constant (A=0 for summer and A=0.5 for winter)
ρ_c	= volumetric heat capacity of ground in J/m^3K
t_0	= duration of year in s (1 Y = $31.5 \cdot 10^6$ s)
$Pass$	= passengers thermal load in W
N	= passenger number
Q_{pass}	= single passenger thermal load in W
Aux	= electrical auxiliaries in W
T_R	= third rail effect in W
M_C	= melting of conductors in W
$R(x_i)$	= line electrical resistance in Ω
I	= current intensity in A
M_{lost}	= mass lost in conductors per hour in $kg/hour$
C_L	= conductors material latent heat in J/kg
P_{ower}	= mechanical power for motion in W
η	= electrical engines efficiency
$E_k(x_i)$	= kinetic energy at x_i in J
$E_p(x_i)$	= potential energy at x_i in J
$V(x_i)$	= train speed at x_i in m/s
z_i	= actual position of train in the z axis
z_{i-1}	= previous position of train in the z axis
$M_{W,i}$	= i wagon mass in kg

Simbol	Description
R_{Energy}	= recovered energy in J
$RECOV$	= recovery rate $0 \leq e \leq 1$
$E_k(x_{i-1})$	= kinetic energy at x_{i-1} in J
$E_p(x_{i-1})$	= potential energy at x_{i-1} in J
$P_{ower}(x_i)$	= power generated by the motors at x_i in W
$F(x_i)$	= forces over the train at x_i in N
$\bar{M}_I$	= mean train inertial mass in kg
$a(x_i)$	= train acceleration in m/s^2
F_R	= rolling friction force in N
$K1$	= kinematic friction coefficient
g	= gravity acceleration in m/s^2
F_D	= aerodynamic drag force N
A_F	= train frontal area m^2
C_D	= drag coefficient
α_T	= tunnel parameter
F_C	= force due track curve in N
F_S	= force due track slope in N
dh	= track hight difference with equal slope in m
dl	= track length with equal slope and curve radius in m
r	= curve radius in m

IV. MANUAL DE USUARIO DEL SISTEMA MODENERGY:
Simulador de Balance Termal en Túneles de Metro

CENTRO DE
MODELAMIENTO
MATEMATICO

Modenergy V3.0 User Guide

Last Updated: 2006-09-24

Table of contents

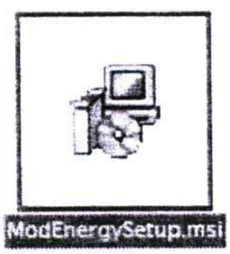
Chapter 1: Installation

Requirements

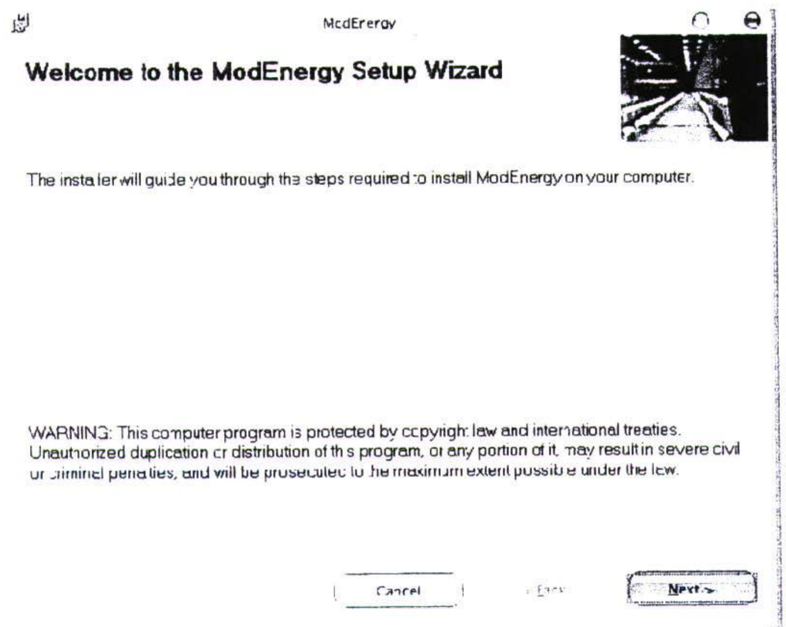
1. Microsoft® Windows 2000 with Service Pack 4, Windows XP Professional or Home Edition with Service Pack 2, or Windows XP Tablet PC Edition, Windows 2003 Server.
2. .NET Framework Version 1.1 Redistributable Package download from (http://www.microsoft.com/downloads/details.aspx?FamilyID=262d25e3-f589-4842-8157-034d1e7cf3a3&displaylang=en)
3. 2 GHz Pentium IV class processor or better
4. 128MB of RAM min, 256 MB or greater recommended
5. Up to 2 MB of available hard-disk space

Normal installation

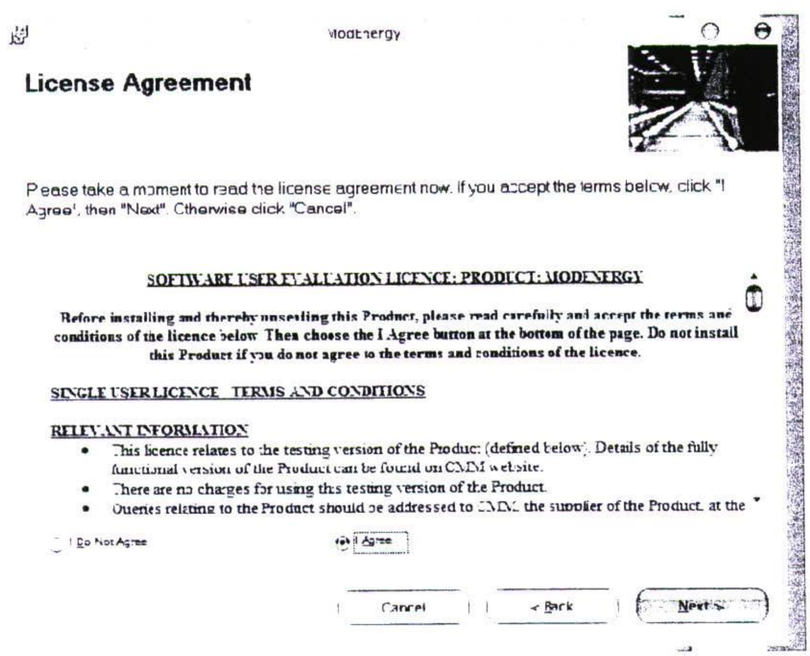
1. For a successful installation of ModEnergy Software, administrative access to your PC may be required, which is normally provided by your IT department.
2. Click the Download Now button. A dialog box will appear asking you where to save the Installer.
3. Save the Installer on your desktop, and wait for it to download completely.
4. An Installer icon will appear on your desktop. Double-click on it.



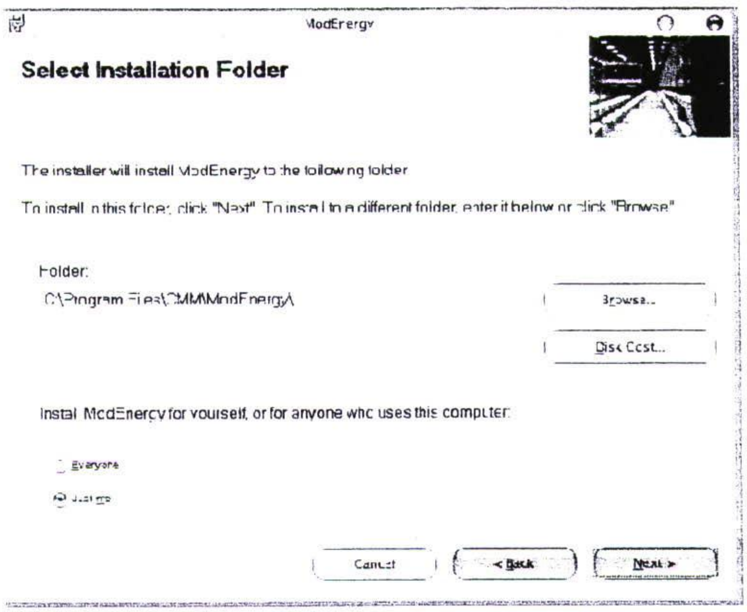
5. The installation program will be started automatically.



6. Read and accept the license agreement

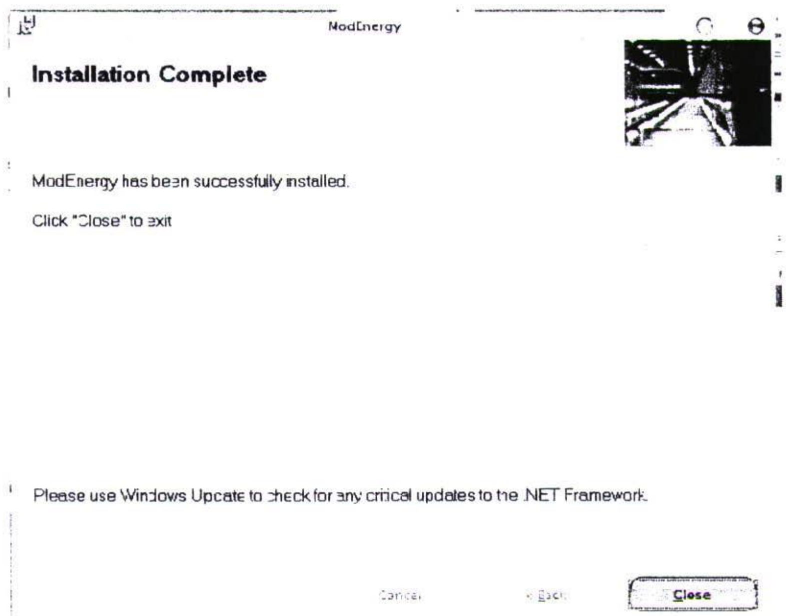


7. Determine the place on your hard disk where you want Modenergy to be installed. Normally, the proposed “c:\program files\CMM\Modenergy\ “ will do fine. Or else, just browse to the directory where their current Modenergy version is found and select that as destination directory.

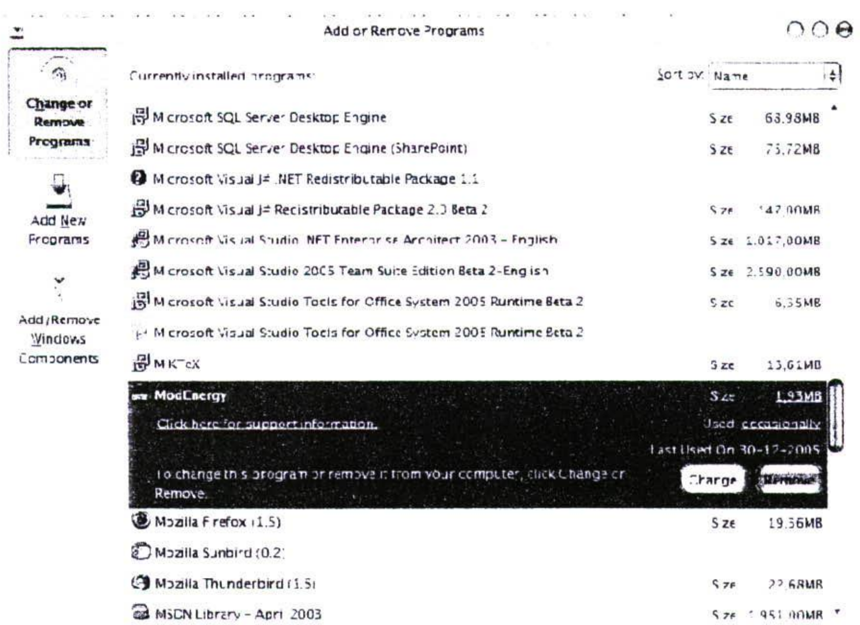


8. Select 'Next' and you're done! The installer will take care of all the work.

9. When installation status becomes ok, select close button and start to using the software



10. If you need to remove Modenergy go to control panel and choose add or remove programs, select Modenergy and remove.



Chapter 2: Concepts and basics

Introducing ModEnergy V3.0

ModEnergy is powerful and easy-to-use software for a thermal simulation of a Metro system, designed for the demanding needs of the project, the software is based in our model, the way it was conceived and how one can use it to deal with "what-if" scenarios. We have made some simplifications, but this actual model can be improved, instead of using empirical parameters for the model, we decided that the best approach was from a strictly physical point of view. Thus the system is modeled as dynamic systems (the trains) that move between stations and this system has certain energy inputs and outputs. Then we have the tunnel system that interacts with the energy exchanges that rise from the train system.

- **Train model**: The train was modeled as a dynamic system that moves along rails. The train has a certain mass (tare weight, load and rolling inertial mass) and one wants it to follow a certain acceleration and deceleration curve. Forces that act on the train are: inertia, rolling friction, air drag. From the basic equations one can calculate the required force for the train to accelerate and thus the input power as well as the energy losses.

- **Speed / distance track:** From basic kinematics, we use the speed versus distance for this simple model. We had to use a 1 meter interval to have good enough approximations. One can input and change parameters such as: mass (empty, passengers and inertia), the acceleration versus distance profile, rolling resistance, drag coefficient and the power dissipated by auxiliaries. Braking efficiency actually can be modified.

- **Kinematics results:** Besides the speed versus distance profile, one also obtains the force necessary to accelerate the train and also the different

losses, including braking losses. These are presented both as kW as well as kJ per meter. From these results it is evident that, except during braking, one important loss to the tunnel is due to auxiliaries. As the train moves along the track, there is power dissipating as heat. This is then calculated as energy dissipated per meter of track when a train passes. For the moment, we suppose the track is horizontal and straight. It should not be too difficult to incorporate slopes and curves. The basic idea of this approach was to have a good breakdown of the different forces that act upon the train and then compare these with real cases of study.

New Features and Fixes

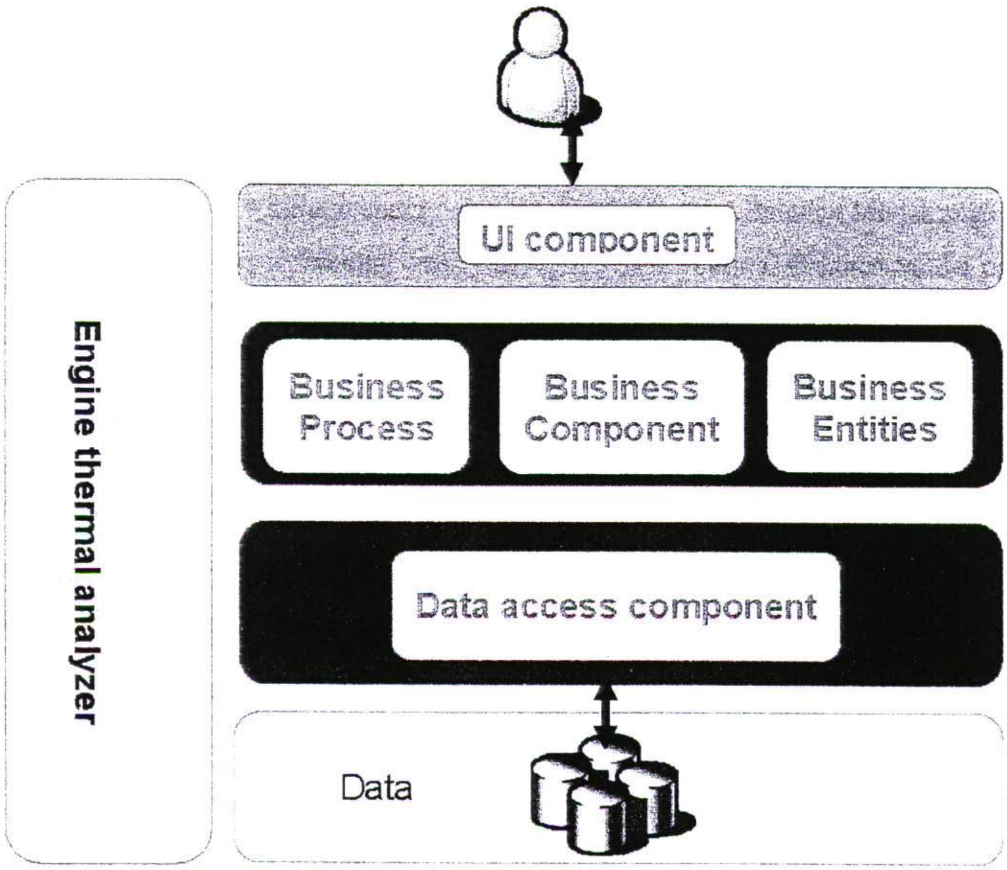
Modenergy has been redesigned for improvement the new characteristics.

Here's what's new in ModEnergy V3.0:

- UI - We developed a new UI, improvements to product usability including descriptive object, redesigned options menu, working area and data management.
- **Fixes bug** - Fix crucial Core layout architecture bugs, paving the way for a more maintainable, performant, and extensible future.
- **New characteristics** – like:
    - engine thermal analysis 3.0
    - adding train parameters
    - adding Lines with non homogeneous Stations
    - adding trains with non homogeneous car
    - adding curve and slope
- **Pdf Report**

ModEnergy V3.0 Architecture

The new ModEnergy architecture using three tier model:



Correspondence between Software and Thermal model

Distance (m) = distance profile vector in x axis by one or all station

Speed (m/s) = Speed profile vector in x axis by one or all station

Time interval (s) = t_i-t_{i-1}=2/ (Vi - V_{i-1})*(x_i-x_{i-1})

Accel (m/s2) = acceleration = (Vi - V_{i-1})/(ti - t_{i-1})

Kinetic Energy (J) = kinetic energy at xi, in J (ref: Thermal Balance Model page 14)

Potential Energy (J) = potential energy at xi, in J (ref: Thermal Balance Model page 14)

Inertial Force (N) = Inertial Forces (ref: Thermal Balance Model page 15)

Aerodynamic Drag Force (N) = (ref: Thermal Balance Model page 16)

Curve Force (N) = Force due to Track Curve (ref: Thermal Balance Model page 16)

Slope Force (N) = Force due to Track Slope (ref: Thermal Balance Model page 17)

Mechanical Power (W) for motion (ref: Thermal Balance Model page 15)

Train Heat (Qt) = (ref: Thermal Balance Model page 11-14)

Earth Temperature = earth temperature at the wall of the tunnel, in °C (ref: Thermal Balance Model page 10)

Air Temperature = air temperature inside the tunnel in °C. is the result of the thermal balance shown in the Thermal Balance Model page 6.

A First Look at Modenergy

When you first open Modenergy, you see the following areas:

Menus

The menu contains two shortcuts:

- **Exit menu** - Close the application.
- **Help menu** - Contains documentation and informational links.
    - About - Informational dialog about Modenergy, including the current software version number. Other information that is provided includes the copyright and team developer.